

Role of isospin dependent mean field in pion production in heavy ion reactions

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The importance of a isospin dependent nuclear mean field (IDMF) in regard to the pion production mechanism is studied for the reaction $Au + Au$ at 1 GeV/nucleon using the Quantum Molecular Dynamics (QMD) model. In particular, the effect of the IDMF on pion spectra and the charged pion ratio are analyzed. It is found that the inclusion of a IDMF considerably suppresses the low- p_t pions, thus, leading to a better agreement with the data on pion spectra. Moreover, the rapidity distribution of the charged pion ratio appears to be sensitive to the isospin dependence of the nuclear mean field.

Keywords: Isospin dependent mean field, pion production, QMD, 1 A.GeV

Au on Au reaction

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I. INTRODUCTION

The investigation of particle production is a well established method to probe the hot and dense nuclear matter which is produced in collisions between heavy nuclei. The collision dynamics is rather fairly understood within transport model approaches. At incident energies around 1 A.GeV one finds that the pion production is the dominant channel by which the hot, compressed matter de-excites. Pionic observables such as yields, spectra and flow have been measured at GSI (FOPI [1], KaoS [2,3]) and LBL [4–6]. One, however, finds that transport models such as QMD and BUU in general overestimate the abundance of low energy pions as well as the charged pions multiplicities [1,7,8]. In addition, this discrepancy is most prominent in heavy colliding systems like Au , as compared to light systems such as Ni [9]. One characteristic aspect of such heavy systems is the high neutron-proton asymmetry effect. Essentially due to this asymmetry factor $I = \frac{N-Z}{A}$, in the case of heavy systems, one generally finds for the total pion yields $N(\pi^-) > N(\pi^0) > N(\pi^+)$. On the other hand, for light systems one expects the pion abundances to be more or less equally distributed, i.e. $N(\pi^-) \simeq N(\pi^0) \simeq N(\pi^+)$. This observed charge dependence of the pion yields is mainly due to the isospin dependence of the pion production cross sections which can be well understood within the isobar model [10–12] as most of the pions produced at intermediate energies originate from Δ -decays.

Normally, although a isospin dependence is duly included in the baryon-baryon collision process, these baryons comprising nucleons, Δ 's and N^* 's propagate in an isospin independent mean field. As most of the pions, particularly the low energy ones, result from Δ -decays the general nature of the production/re-absorption and the propagation of Δ -resonances are important. The inclusion of a isospin dependent mean field (IDMF) will certainly affect the reaction dynamics of nucleons and resonances leading to possible differences in pion yields. This is due to the fact that the various charges of nucleons and resonances will be affected in a different way by the isospin dependent mean field during their propagation. This isospin dependence makes neutrons more energetic than protons.

Thus, with other properties remaining the same, one expects that with inclusion of a IDMF the average number $N_{<nn>}$ of n - n collisions will get somewhat reduced while the average number $N_{<pp>}$ of p - p collisions will get slightly enhanced. At low incident energies, it is found [13,14] that the IDMF strongly affects observables such as the collective flow and the pre-equilibrium p/n ratio. Therefore, it is of general interest to analyze the role of the IDMF in the context of pion production in heavy ion reactions at SIS energies.

In view of this we make our first exploratory study on the role of a isospin dependent mean field on the pionic observables such as p_t -spectra and the π^-/π^+ ratio.

II. ISOSPIN DEPENDENCE OF PION PRODUCTION

To analyse the effect of the isospin dependence on the pion production process we make use of the Quantum Molecular Dynamics (QMD) model [15] which is well described in our earlier works [17,8].

Pions are produced mainly by resonance decays, and this pion production process is implemented in the model in the following way. Nucleons while propagating shall collide stochastically if the distance between the centroids of the two Gaussian wavepackets is less than $d_{\min} = \sqrt{\sigma_{\text{tot}}(\sqrt{s})/\pi}$. This collision process is implemented using Monte Carlo methods and the effect of the Pauli exclusion principle is duly taken into account. For the inelastic nucleon-nucleon channels we include the $\Delta(1232)$ as well as the $N^*(1440)$ resonance. In the intermediate energy range the resonance production is dominated by the Δ , however, the N^* yet gives non-negligible contributions to the high energetic pion yield [16]. The resonances as well as the pions originating from their decay are explicitly treated, i.e. in a non-perturbative way and all relevant channels are taken into account. In particular we include the resonance production and rescattering by inelastic NN collisions, the one-pion decay of Δ and N^* and the two-pion decay of the N^* and one-pion reabsorption processes. (For details see Ref. [17].) The isospin dependence of the pion production cross sections is duly included in the model. Thus one is able to understand the observed charged

dependence given by $N(\pi^-) > N(\pi^0) > N(\pi^+)$. For the Au+Au system, we obtain the ratios $\pi^- : \pi^0 : \pi^+ = 1.37 : 1 : 0.71$ for the respective multiplicities, which then gives $\pi^-/\pi^+ = 1.95$. Finally, the pions thus produced are guided essentially by the Coulomb interaction between the pions and baryons.

It may be said here that the pion propagation can, in principle, be also affected by the contribution arising from the effect of nuclear medium, i.e. from the collective ΔN^{-1} and NN^{-1} excitations, on the pion dispersion relation. However, it is shown in a recent study [17] that only weak corrections, i.e. a small in-medium pion-nucleus potential, are required in order to obtain a realistic description of pionic observables. In addition, also in other works [18,19] it was found that the high energy part of the pion spectrum is not much affected by these medium corrections. A more sophisticated treatment of collective pionic excitations within the transport approach was proposed in Ref. [20], which was subsequently applied to heavy ion collisions in Ref. [21]. However, as discussed in Ref. [22], it is rather questionable if the simple ΔN^{-1} (and NN^{-1}) model yields a reliable pion dispersion relation. Further, the results of Ref. [21] indicate that the influence of collective excitations on pionic observables is small and tends to enhance the pion yields with respect to the standard approaches and the experimental findings. Moreover, in this exploratory study we wish to concentrate on the role of the IDMF in pion production. Hence, we omit the medium effects of the charge dependence of pion production in the present work.

Now, coming to the baryon propagation part, the transport models like QMD normally propagate the nucleons and resonances in a density and momentum dependent nuclear mean field and as well include the Coulomb interaction among the charged particles. In the present study we consider in addition to the above stated components a isospin dependent contribution to the total mean field. Thus, one has,

$$V_i = V_{\text{symm}}(\rho, |\mathbf{p}|) + V_{\text{Coul}}^i + V_{\text{asym}}^i(\rho, I) \quad (1)$$

where i stands for any one of the nucleons or resonances. The isospin dependent potential V_{asym}^i is determined following Ref. [14] as

$$V_{\text{asym}}^q = \frac{\partial}{\partial \rho_q} \epsilon_{\text{asym}} \quad ; \quad q = n, p \quad (2)$$

where $\epsilon_{\text{asym}} = \rho S_{\text{potn}}(\rho_o) F(\rho/\rho_o)$ and $S_{\text{potn}}(\rho_o)$ is the potential part of the nuclear symmetry energy at nuclear matter saturation density ($\rho_{\text{sat}} = 0.16 \text{ fm}^{-3}$). The density dependence of the IDMF is taken to be $F(\rho/\rho_o) = (\rho/\rho_o)^\gamma$. The strength of the density dependence varies widely among the theoretical studies [23–27]. For our present qualitative investigation, we choose two particular values, $\gamma = 0.3$ and $\gamma = 2.0$. Having obtained the IDMF for neutrons and protons, we now express V_{asym} for the respective resonances as: $V_{\text{asym}}(n^*) = V_{\text{asym}}(\Delta^0) = V_{\text{asym}}^n$, $V_{\text{asym}}(p^*) = V_{\text{asym}}(\Delta^+) = V_{\text{asym}}^p$, $V_{\text{asym}}(\Delta^{++}) = 2V_{\text{asym}}^p - V_{\text{asym}}^n$ and $V_{\text{asym}}(\Delta^-) = 2V_{\text{asym}}^n - V_{\text{asym}}^p$. Thus, both, nucleons and resonances propagate in an isospin dependent mean field.

Consequently, there shall appear – with the other conditions being the same – a smaller number of n – n and n – p collisions, and a slightly enhanced number of p – p collisions. Since π^- are predominantly created in n – n collisions via Δ^- and Δ^0 decays, the number of π^- (N_{π^-}) is expected to decrease. On the other hand, as π^+ are mainly created in p – p collisions via Δ^{++} and Δ^+ decays, N_{π^+} may slightly increase. Therefore, the charged pion ratio π^-/π^+ may effectively decrease. But, we need to take into account the effect of re-absorption process as well, which sort of counterbalances the effect due to the IDMF on pion production. In addition, in the case of π^+ , both n – p and p – p collisions contribute to N_{π^+} via Δ^+ decay. As $N_{<np>} > N_{<pp>}$ there may as well be a slight reduction in N_{π^+} at the end of the reaction. The final outcome of the interplay of these effects in regard to pionic observables is discussed in the following section.

III. RESULTS AND DISCUSSIONS

In this section we discuss the results as obtained from simulations made including an isospin dependent mean field in the baryon propagation part. All the calculations pertain to the $Au + Au$ reaction at 1 A.GeV and use the standard momentum dependent Skyrme force which corresponds to a soft equation of state, hereafter referred to as SMD force.

As expected, we find that the average number of collisions are modified due to the presence of a IDMF. It is found that average number of n - n collisions, $N_{<nn>}$, decrease by about 10%, while $N_{<pp>}$ increase by about 5%. As a result, it can be seen from Fig. 1 that, the total pion multiplicity N_π obtained for zero impact parameter, $b = 0$, decreases by about 20% at midrapidity. Moreover, though one sees that the reduction in N_π slightly increases with increase in the value of parameter γ , which signifies the density dependence of the symmetry energy; the dependence of N_π on γ is not so prominent at high incident energies considered here. In addition, it may be said here that though the total pion number at $b = 0$ decreases from ~ 58 to ~ 50 , the theoretical results obtained for charged pion multiplicity are still overestimated [1,8] as compared to the experimental data.

It is known [28] that the high energy pions belong mostly to the early, compressed phase of the nuclear reaction. Hence, these pions undergo relatively less scattering as compared to the low energy pions, and thereby, one expects high energy pions to be less affected by the isospin dependence of the mean field. This aspect is illustrated in Fig. 2, where the pion transverse momentum p_t distribution calculated at midrapidity with $b = 0$ is shown. A substantial reduction over the low- p_t part due to the IDMF can be noted. In contrast, the high- p_t part remains more or less the same. Further, a similar suppression of low- p_t pions is also found in the case of non-central collisions. It maybe recalled here that transport models like QMD overestimate the low energy part of pion spectra. Now, with inclusion of the IDMF, we expect that this overestimation of model calculations as compared to the data to be reduced. Toward this purpose, we performed simulations pertaining to the minimum bias condition for a particular value of $\gamma = 2$. Results obtained for the charged pion spectra are compared in Figs. 3 and 4 to the FOPI data [1]. It is satisfying to note that results obtained with the IDMF are closer to the FOPI data than those obtained with $V_{\text{asym}} = 0$, particularly over the low- p_t part. In addition, the effect of the IDMF is more significant on the π^- spectrum than on π^+ . Thus, for a quantitative description of pion yields and spectra, we need to include the isospin dependence of the mean field.

Another quantity which is sensitive to the isospin dependence is the charged pion ratio

π^-/π^+ . The study of the charged pion ratio is of importance and current interest since one can, in principle, extract information regarding the size of the participant zone during its compression and expansion stages. In particular, the observed energy dependence of π^-/π^+ – that is, the value of this ratio decreases from about 3.0 to 0.9 as pion kinetic energy increases from ~ 50 MeV to ~ 350 MeV, and remains almost constant at higher energies – is shown to be due to the Coulomb potential [8,29,30], which is opposite in nature for π^+ and π^- . With the inclusion of a IDMF we expected the ratio to decrease, particularly over the low energy region. However, we found that in practice the decrease is not substantial enough to illustrate the role of IDMF. This may be due to, firstly, that there is a net reduction in low- p_t π^+ 's as these positively charged pions are also produced in $n - p$ collisions, and secondly, that the low- p_t pions undergo more production-reabsorption cycles before they freeze out which may wash out the isospin effects.

However, the effect of the IDMF on π^-/π^+ is more clearly seen when the charged pion ratio is analysed as a function of the normalized center-of-mass rapidity Y^0 . Results obtained with $b = 0$ are shown in Fig. 5. The error bars quote the statistical uncertainty of the calculations which is due to the event number. Quite interestingly, similar to the energy dependence, there appears a systematic Y^0 -dependence of the π^-/π^+ ratio where we obtain in the case of no asymmetry dependence, i.e. $V_{\text{asym}} = 0$, $\pi^-/\pi^+ > 1.95$ over the midrapidity region and the ratio decreases with increasing $|Y^0|$. This Y^0 -dependence is essentially due to the Coulomb interaction. This is also illustrated in the same figure, where one finds that, in the absence of the Coulomb interaction, the ratio remains more or less constant, i.e. $\pi^-/\pi^+ \sim 1.8$ which is indicated by the horizontal line in Fig. 5. Furthermore, once the IDMF is included, the charged pion ratio gets significantly suppressed over the midrapidity region while the distribution remains more or less the same beyond the midrapidity region. With an increase in the value of γ , Eq. (2), the amount of suppression slightly increases. In addition, there appears a double peaked structure, even at $b = 0$, which is due to the isospin dependence of the nuclear mean field. Furthermore, this structure appears to be sensitive on the density dependence of the isospin dependent interaction. Thus, this particular ob-

servable clearly illustrates the effect due to Coulomb interaction and the IDMF. A recent preliminary analysis [31] of the FOPI data for 1 A.GeV Au on Au collisions indicates such a double peaked structure for semi-central as well as for most central collisions. In semi-central collisions this structure is probably due to an incomplete stopping and thermalization of the pions and can be qualitatively explained by the standard approach. To illustrate this effect we show in Fig. 6 the π^-/π^+ ratio for a central ($b=1$) and a semi-central ($b=6$) collision with both calculations performed without an isospin dependence of the nuclear mean field. As already seen in Fig. 5 there exists only one single peak for $b=1$. Thus the reduction of the π^-/π^+ ratio at midrapidity in central collisions can probably be regarded as a signature for the importance of the IDMF in the pion production mechanism at SIS energies.

IV. SUMMARY

To summarize, we have made an exploratory study on the importance of a isospin dependent nuclear mean field (IDMF) concerning the pion production mechanism in intermediate energy heavy ion reactions. It is found that due to the different isospin charges of nucleons and resonances, the average number of collisions gets modified and hence, the pion yield. In particular, the low energy pions get significantly suppressed rendering a better agreement of calculated pion spectra with the FOPI data. We have also analysed the rapidity distribution of the charged pion ratio where due to the effect of the IDMF, one finds a substantial reduction of the π^-/π^+ ratio over the midrapidity region in central collisions. This particular observable seems to illustrate clearly the effects due to Coulomb force and the IDMF. Therefore, our present study strongly suggests that at the quantitative level, it is quite important to take into account the isospin dependence of the nuclear mean field.

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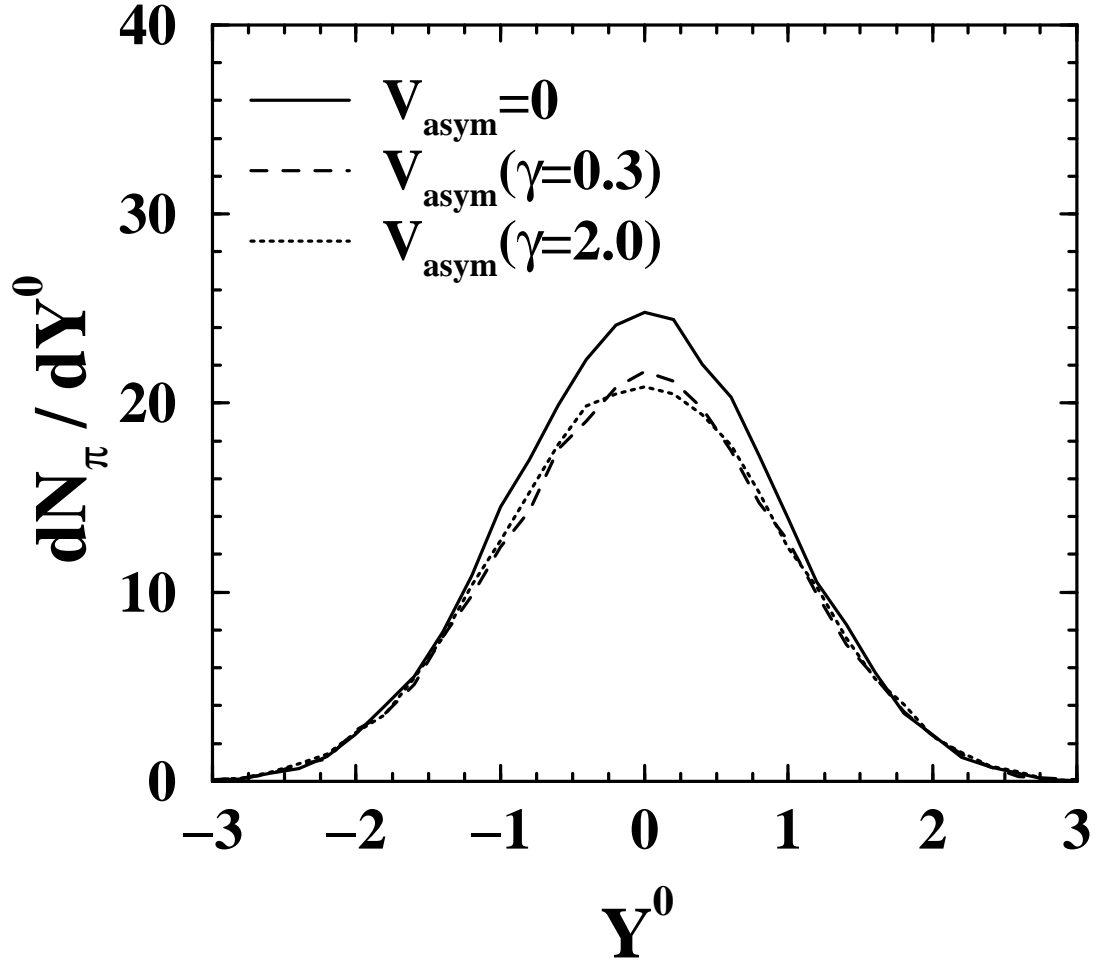


FIG. 1. The total pion multiplicity N_π in a central ($b = 0$) $Au + Au$ reaction at 1 A.GeV is shown as a function of the normalised rapidity $Y^0 = (Y_\pi/Y_{\text{proj}})_{\text{cm}}$. The calculations are performed with (dashed, dotted) and without (solid) an isospin dependent nuclear mean field.

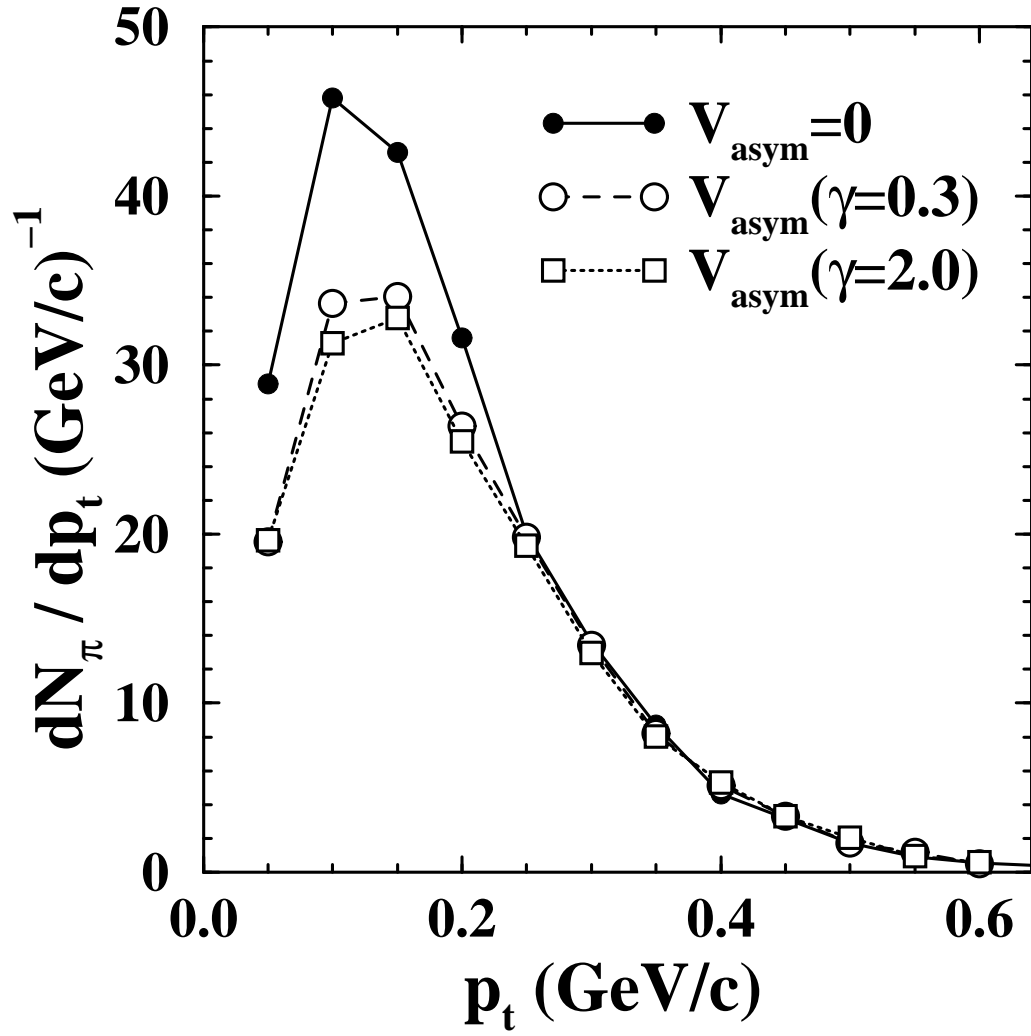


FIG. 2. Pion transverse momentum p_t distribution calculated at midrapidity $-0.2 \leq Y^0 \leq 0.2$ for the same reaction as in Fig. 1.

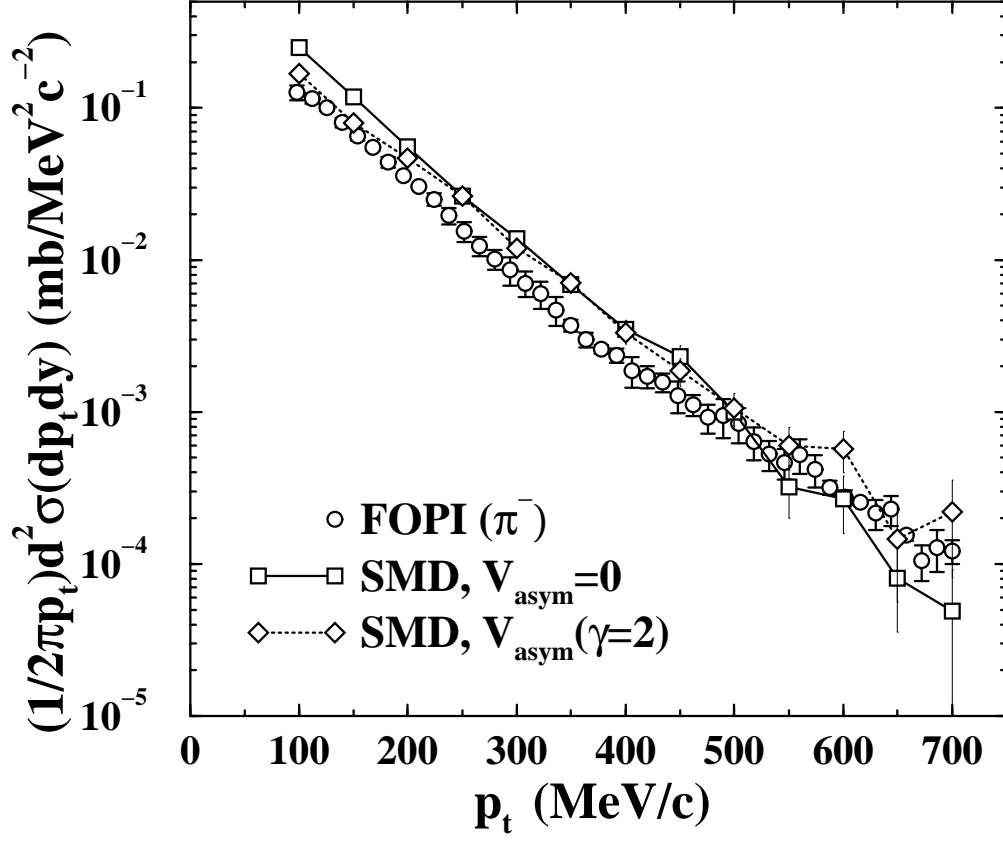


FIG. 3. The π^- p_t spectrum in a 1 A.Gev $Au + Au$ reaction obtained at midrapidity under *minimum bias* condition is compared to the FOPI data of Ref. [1].

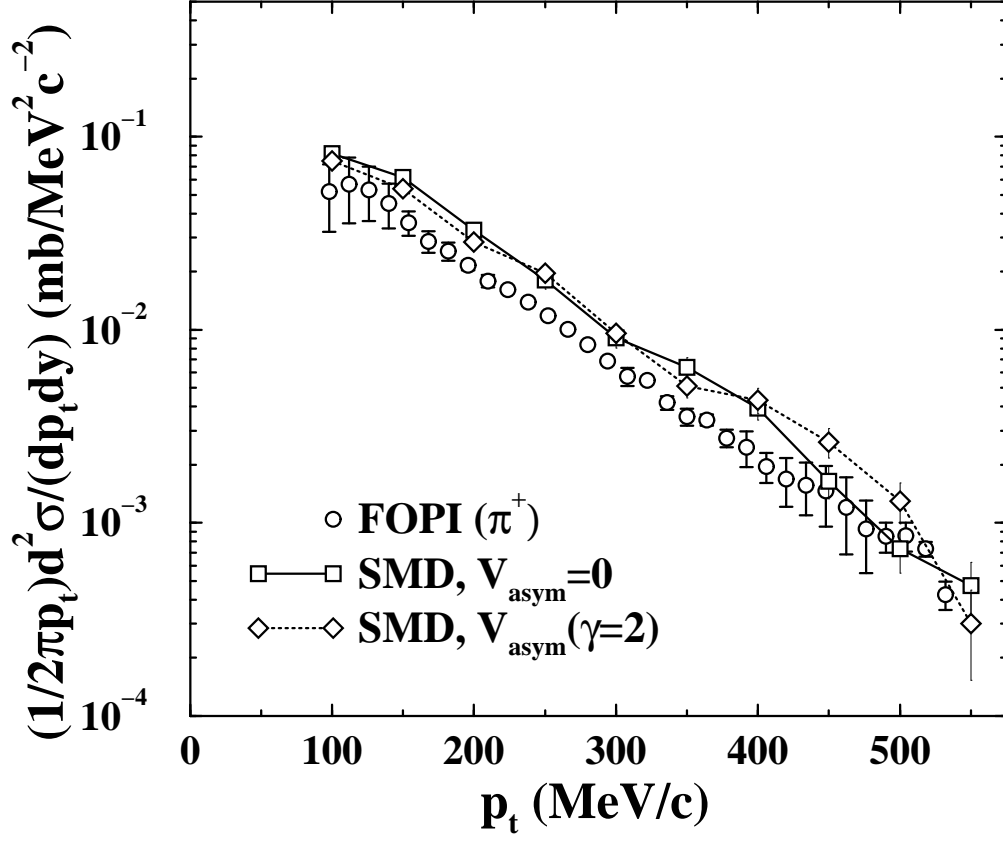


FIG. 4. The π^+ p_t spectrum in a 1 A.GeV $Au + Au$ reaction obtained at midrapidity under *minimum bias* condition is compared to the FOPI data of Ref. [1].

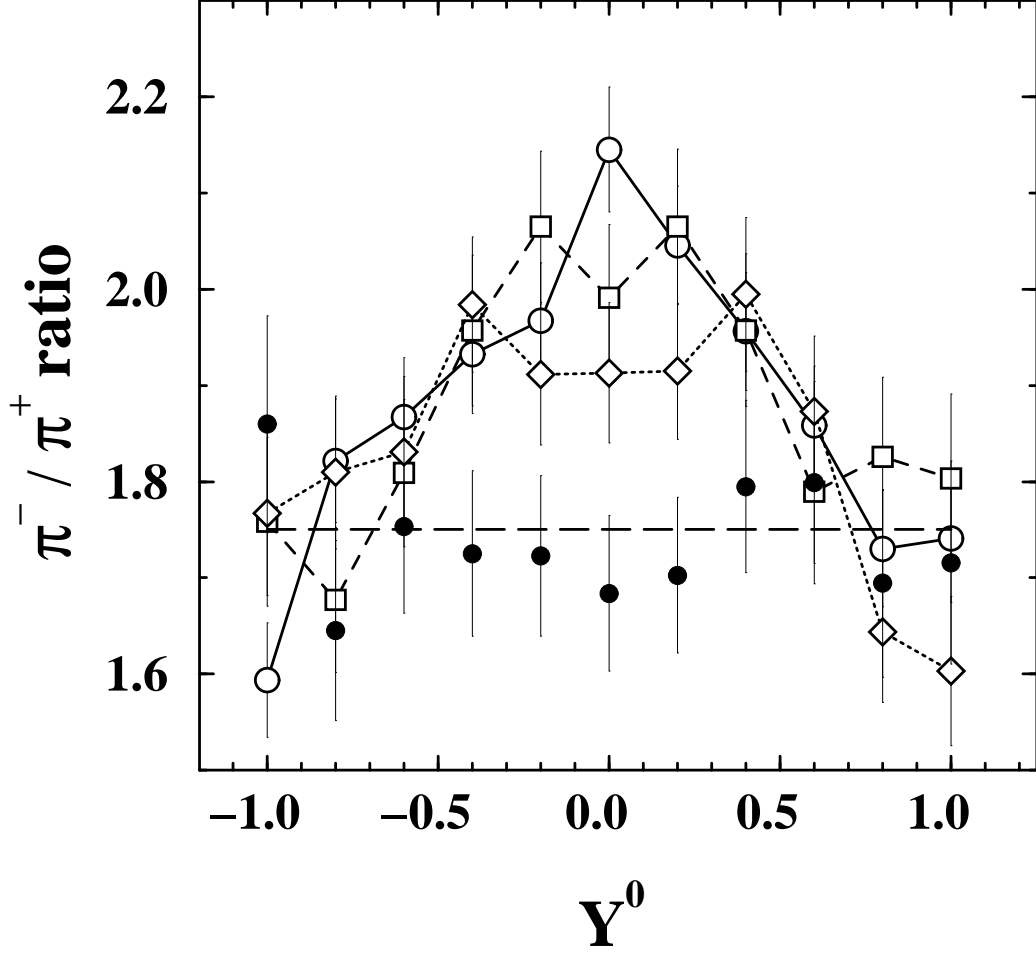


FIG. 5. Dependence of the charged pion ratio on the normalized rapidity calculated in a central ($b = 0$) 1 A.GeV $Au + Au$ reaction. The calculations are performed without (open circles) and including the isospin dependence of nuclear mean field. Here squares refer to the IDMF given by the parameter $\gamma = 0.3$ and diamonds to $\gamma = 2.0$. The filled circles correspond to a calculation without both, the isospin dependence and the pion-baryon Coulomb interaction. The horizontal line refers to the average value of the charged pion ratio obtained in this calculation.

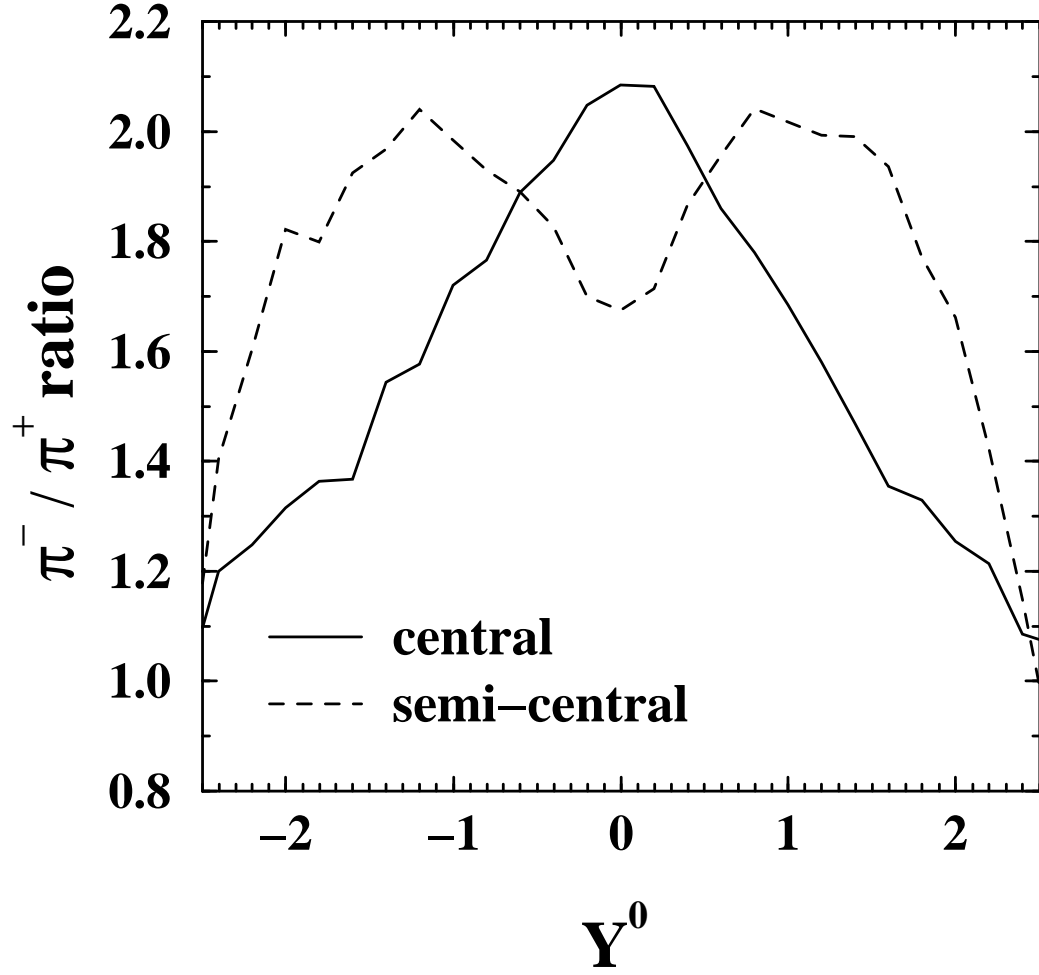


FIG. 6. Centrality dependence of the charged pion ratio on the normalized rapidity in a 1 A.GeV $Au + Au$ reaction. The calculations for the central ($b=1$ fm) and the semi-central ($b=6$ fm) reaction are performed with the standard SMD force, i.e. without an isospin dependence of nuclear mean field.